Provision of Ancillary Services with Variable Speed Wind Turbines

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***Abstract*—In recent years, the amount of wind turbines in the power system has increased tremendously. As the current wind turbines do not participate in the provision of ancillary services such as frequency control and voltage control, this may compromise the proper functioning of the electric power system. However, since the modern wind turbines are equipped with a power-electronic converter, they can assist in the provision of ancillary services. To achieve this, additional control loops have to be added to the wind turbine controller. In this paper, an overview of the different ancillary services is given. The ability to provide them with wind turbines is discussed. Since frequency and voltage control are the most important, these two services are further elaborated. It can be concluded that wind turbines are suited to provide frequency control, especially when they are operated slightly below their maximum power point. They can also assist in voltage control, while operation in the maximum power point is usually possible, so few energy is lost. These are important outcomes, since wind turbines which provide ancillary services can contribute in allowing a higher penetration of renewable energy in the power system without compromising its proper functioning.**

***Index Terms*—Wind energy, ancillary services, frequency control, inertial response, voltage control**

I. Introduction

Global environmental concerns have led to the increased use of renewable energy produced by PV panels, wind turbines, etc. In recent years, the amount of wind power capacity has grown steadily. It is expected that the total wind power capacity in Europe will increase to 160 GW by 2016 [1]. Considering this growth, it is likely that wind energy systems will supply a major part of the future electricity generation from renewables.

This increase in wind power penetration raises concerns about the secure and reliable operation of the power system. The intermittency of the wind causes a variety of problems. Due to varying wind conditions, fluctuations in the output power of wind turbines arise. To maintain the balance of the power system, conventional units must maintain additional reserves to cope with an unexpected drop in the wind speed, which leads to increased costs [2].

Also, difficulties with frequency control may arise when the penetration of wind turbines increases. The common variable-speed wind turbines have little or no natural inertial response and do not participate in frequency control [3]. Today, also other ancillary services such as voltage control, are only provided by the conventional units, which is an unsustainable situation with increasing renewable energy penetration levels.

However, many of the aforementioned problems can be solved by using an appropriate control for the wind turbines. Variable speed wind turbines are equipped with a power-electronic converter to inject the generated power in the grid. By using different control strategies for this converter, a broad range of ancillary services can be provided. In literature, several strategies can be found which enable wind turbines to provide emulated inertial response or participate in primary control. Also, methods to enhance voltage and transient stability or to provide voltage regulation are available.

The topic of this paper is the provision of ancillary services with wind turbines. First, an overview of the different ancillary services is given. Second, the two most important services, frequency and voltage control, are discussed in detail. The focus is on the ability to provide these services with wind turbines.

II. Overview of Ancillary Services

A. Definition

Ancillary services are defined by Eurelectric as *"all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality"* [4]. Ancillary services are procured by the system operators and are provided by the grid users, such as generators or consumers.

Of course, many different services can be regarded as ancillary services, so different authors/organizations list different services. In this paper, only ancillary services that can be provided by generating units are considered [4]:

- Frequency control
- Voltage control
- Congestion management
- Improvement of power quality
- Reduction and compensation of power losses
- Black start and island operation capability

From these, frequency and voltage control are the most important services and are described in detail in the next sections.

B. Frequency control

As electricity cannot be stored easily in large quantities, the production must always equal the consumption. This balance guarantees a stable operation of the electricity grid at a constant frequency of 50 Hz. When there is a sudden change in the production or consumption, frequency deviations occur.

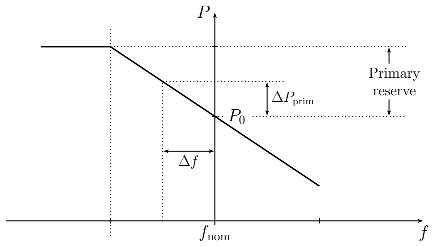


Fig. 1. Frequency control: P/f droop function.

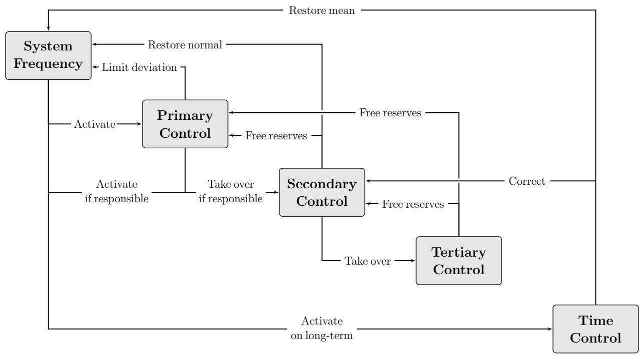


Fig. 2. Overview of frequency control.

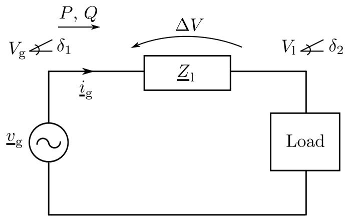


Fig. 3. Simple system to study the power flow equations.

To maintain and/or restore the frequency, the output of the generators must be rapidly increased or decreased.

In the European synchronous electricity grid, the frequency regulation is achieved in three stages: primary, secondary and tertiary control.

1) Primary frequency control: Primary control maintains the balance between power generation and consumption when a deviation occurs. It is automated and within seconds ($\sim$ 15 s - 30 s) the active power output of the generators can be increased or decreased. The change in active power output due to the functioning of the primary control, P_{prim}, is proportional to the deviation of the grid frequency:

$$P_{\mathrm{prim}} = K_{\mathrm{P}} \left(f_{\mathrm{nom}} - f \right) \tag{1}$$

where f is the actual grid frequency, f_{nom} is the nominal grid frequency (50 Hz) and K_{P} is determined by the slope of the droop characteristic, shown in Fig. 1. To achieve this change in active power output, primary or frequency containment reserves have to be maintained at any time. After the activation of these reserves, the power balance is restored at a frequency deviating from the nominal value.

2) Secondary frequency control: Secondary control is used to restore the grid frequency back to the nominal frequency. Furthermore, the desired energy exchange between the different control areas is maintained by this control. Secondary control is only activated in the control area where a power deficit exists and is activated automatically. It starts after a few seconds and is usually completed after 15 min. In this case, secondary or frequency restoration reserves are needed. An automatic PI-control function that is applied at the TSO control center activates the secondary reserves. If there still exists a frequency deviation after the activation of these reserves, secondary control gives way to tertiary control.

3) Tertiary frequency control: The main function of the tertiary control is to restore the required level of operating reserves (primary and secondary reserves). Tertiary or replacement reserves are maintained at any time and are activated manually by the TSO about 15 min after the initial deviation. Tertiary control copes with persistent control deviations after production outages or long-lasting load changes. The tertiary reserves can be situated in the control area where the power deficit exists or in other areas of the synchronous area.

4) Time control: If the mean system frequency in the synchronous zone deviates from the nominal frequency of 50 Hz, this results in a discrepancy between synchronous time and universal coordinated time (UTC). Therefore, the synchronous time is calculated and its correction is organized centrally. Correction involves the setting of the set-point frequency for secondary control at 49.99 Hz or 50.01 Hz, depending upon the direction of correction, for full periods of one day.

The different functions of primary, secondary, tertiary and time control are summarized in Fig. 2

C. Voltage control

In an AC power system, the voltage and current are normally not in phase. Hence, reactive power will flow. Reactive power is absorbed by inductive components (e.g., transformers, overhead lines, induction machines, ...) and generated by capacitive components (e.g., over-excited synchronous machines, capacitors, ...).

The active and reactive power flows in the network cause voltage drops over the network impedances. These voltage drops can be compensated by supplying active and/or reactive power. To study the influence of the active and reactive power on the voltage, the simplified system of Fig. 3 is considered.

The complex power $\underline{S}$ injected by the power source is given by:

$$\underline{S} = \underline{v}_{\mathrm{g}} \underline{i}_{\mathrm{g}}^{*} \tag{2}$$

with $\underline{v}_{\mathrm{g}}$ the voltage of the power source: $\underline{v}_{\mathrm{g}} = V_{\mathrm{g}} e^{j\delta_1}$ in the complex notation, $\underline{i}_{\mathrm{g}}$ the line current and $\underline{i}_{\mathrm{g}}^{*}$ the complex conjugate of $\underline{i}_{\mathrm{g}}$. This power source is connected to a load with voltage $\underline{v}_{\mathrm{l}} = V_{\mathrm{l}} e^{j\delta_2}$ through a line impedance $\underline{Z}_{\mathrm{l}} = R_{\mathrm{l}} + jX_{\mathrm{l}}$:

$$\underline{i}_{\mathrm{g}} = \frac{\underline{v}_{\mathrm{g}} - \underline{v}_{\mathrm{l}}}{R_{\mathrm{l}} + jX_{\mathrm{l}}} \tag{3}$$

The load's phase angle δ_2 can be chosen as zero as voltage angles are relative quantities, therefore, $\underline{v}_{\mathrm{l}} = V_{\mathrm{l}}$. The active and reactive power can be written as:

$$P = \frac{V_{\mathrm{g}}}{Z_{\mathrm{l}}^{2}} \left[R_{\mathrm{l}}(V_{\mathrm{g}} - V_{\mathrm{l}} \cos\delta_1) + X_{\mathrm{l}} V_{\mathrm{l}} \sin\delta_1 \right] \tag{4}$$

$$Q = \frac{V_{\mathrm{g}}}{Z_{\mathrm{l}}^{2}} \left[-R_{\mathrm{l}} V_{\mathrm{l}} \sin\delta_1 + X_{\mathrm{l}}(V_{\mathrm{g}} - V_{\mathrm{l}} \cos\delta_1) \right] \tag{5}$$

A general assumption is that the phase angle variations are limited in the network, hence $\delta_1 \approx \delta_2$, $\sin\delta_1 \approx \delta_1$ and $\cos\delta_1 \approx 1$. By using these approximations, P and Q can be expressed as:

$$P \approx \frac{V_{\mathrm{g}}}{Z_{\mathrm{l}}^{2}} \left[R_{\mathrm{l}}(V_{\mathrm{g}} - V_{\mathrm{l}}) + X_{\mathrm{l}} V_{\mathrm{l}} \delta_1 \right] \tag{6}$$

$$Q \approx \frac{V_{\mathrm{g}}}{Z_{\mathrm{l}}^{2}} \left[-R_{\mathrm{l}} V_{\mathrm{l}} \delta_1 + X_{\mathrm{l}}(V_{\mathrm{g}} - V_{\mathrm{l}}) \right] \tag{7}$$

According to (6) and (7), both active and reactive power have an influence on the grid voltage. However, three different cases can be considered: high-voltage, low-voltage and medium-voltage networks.

The high-voltage (HV) transmission grids are mainly inductive of nature, hence R_{l} is low compared to X_{l}. Therefore, in inductive networks, the expressions for the active power P and reactive power Q reduce to:

$$P \approx \frac{V_{\mathrm{g}} V_{\mathrm{l}}}{X_{\mathrm{l}}} \delta_1 \tag{8}$$

$$Q \approx \frac{V_{\mathrm{g}}}{X_{\mathrm{l}}} (V_{\mathrm{g}} - V_{\mathrm{l}}) \tag{9}$$

A decoupling of P and Q is achieved. The active power P is predominantly dependent on the phase difference (and thus dynamically dependent on the frequency), whereas the reactive power Q is determined mainly by the voltage difference over the line. This leads to the well-known P/f and Q/V linkage in high-voltage networks. Consequently, in high-voltage grids, reactive power is used to control the voltage amplitude.

Low-voltage (LV) networks, on the other hand, are mainly resistive. The active and reactive power flows in the network are then given by:

$$P \approx \frac{V_{\mathrm{g}}}{R_{\mathrm{l}}} (V_{\mathrm{g}} - V_{\mathrm{l}}) \tag{10}$$

$$Q \approx \frac{-V_{\mathrm{g}} V_{\mathrm{l}}}{R_{\mathrm{l}}} \delta_1 \tag{11}$$

Again, a decoupling between P and Q is achieved. Here, P is mainly determined by the voltage difference over the line, so in low-voltage networks, there is a P/V linkage instead of a Q/V linkage. Therefore, in low-voltage grids, using active power to control the voltage is more effective than using reactive power. Furthermore, reactive power injection or absorption in low-voltage grids may lead to increased line losses and reactive power fines due to a bad power factor $\cos\phi$.

In medium-voltage (MV) grids, voltage control is less straightforward. In the conventional power system, the voltage level in the distribution network is controlled by means of on-load tap changers (OLTC). If distributed generators are connected to the medium-voltage network, they should control the voltage by injecting or absorbing active and reactive power,

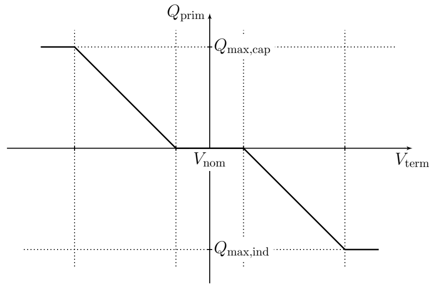


Fig. 4. Voltage control: *Q*/*V* droop function.

since the R/X-value of these networks is usually around one. Therefore, P and Q are no longer decoupled.

Similar to the frequency control, voltage control can be divided into primary, secondary and tertiary control. These types are discussed for the case of high-voltage grids.

1) Primary voltage control: Primary voltage control is an automated control that adjusts the injection of reactive power when the terminal voltage deviates from the nominal value. Generally, droop functions as shown in Fig. 4 are used to stabilize the voltage at the terminal of the unit by injecting or absorbing reactive power. This reactive power control influences the voltage within seconds or even faster. The reactive power set-point of the generator is adjusted by Q_{prim} that is calculated as:

$$Q_{\mathrm{prim}} = K_{\mathrm{Q}} \left(V_{\mathrm{nom}} - V_{\mathrm{m}} \right) \tag{12}$$

where V_{m} is the terminal voltage, V_{nom} is the nominal voltage and K_{Q} is determined by the slope of the droop function.

2) Secondary voltage control: To achieve secondary voltage control, the network operator performs measurements of the voltage in some critical buses that are representative for a certain area. If the voltages are out of range, the voltage reference values for the generators are adjusted to recover a voltage profile in the normalized interval. The time response of the secondary voltage control goes up to one minute and less than several minutes. Similar to secondary frequency control, secondary voltage control is activated automatically in the control center of the network operator where the new voltage reference values are determined. Then, these are sent to the different generators.

3) Tertiary voltage control: Tertiary voltage control is manually activated by the network operator. It is used to optimize the voltage profile and achieve an optimal power flow by adjusting the reference values for the secondary voltage control. The tertiary control acts on a time-scale of about 10 to 30 minutes.

D. Ancillary services provided by wind turbines

In the conventional power system, most of the ancillary services are provided by the large, centralized power plants. With increasing penetration of renewable energy sources, however, more ancillary services will have to be provided by distributed generators such as wind turbines. As variable speed wind turbines usually have a power-electronic converter to inject the generated power in the grid, they are able to provide different ancillary services such as frequency control, voltage control, enhancement of the power quality and even black start. In the next sections, only frequency control and voltage control are further elaborated.

III. Frequency control with wind turbines

In this section, the ability of wind turbines to provide frequency control is discussed.

A. Emulated inertial response with wind turbines

An important difference between frequency control in directly-coupled synchronous generators and variable speed wind turbines is the inertial response, as is explained next.

In an electric power system, the total production P_{gen} always equals the total system load P_{load}. In case of a sudden load or production change, the amount of kinetic energy which is stored in the rotating masses of the generators and motors connected to the system, will change. For a sudden loss of production, this results in a frequency drop. As frequency changes are usually small relative to the nominal frequency, the frequency drop is determined by:

$$\frac{dE_{\text{kin}}}{dt} \approx J f_0 \frac{df}{dt} \approx P_{\text{gen}} - P_{\text{load}} \tag{13}$$

where E_{kin} is the kinetic energy stored in the directly coupled generators and motors, f is the grid frequency, f_0 is the nominal frequency and J is the total system inertia. As the output power of the generators P_{gen} cannot immediately be increased, the initial frequency variation is mainly determined by the release of kinetic energy from the system inertia J. This is called inertial response and has a stabilizing effect on the grid frequency. Few seconds after the disturbance, the primary control increases the power output of the generators to limit the frequency deviation.

However, the situation is different for wind turbines, since the rotational speed Ω of the turbine is often decoupled from the system frequency f by means of a power-electronic converter. Compared to a directly-coupled synchronous generator, the Fixed Speed Induction Generator (FSIG) has lower inertial response due to the reduced coupling between the induction generator rotor speed and the system speed, which is caused by the slip s of the generator [5]. For the Doubly Fed Induction Generator (DFIG), only a very limited inertial response is obtained due to the controlled converter in the rotor circuit. In the Full Scale Converter (FSC) type, the rotational speed of the generator is completely decoupled from the grid frequency by means of a back-to-back converter. As a result, no inertial response is obtained for FSC wind turbines [5].

Today, only variable-speed wind turbines are built (DFIG and FSC), so when wind turbines start to replace the conventional production, the total system inertia decreases. However, the rotor of a wind turbine contains as much kinetic energy as a directly coupled generator of the same size [6]. When an appropriate control loop is implemented in the power converter, this kinetic energy may be used to emulate an inertial response and support the system inertia. There exist two common strategies to emulate an inertial response: the synthetic inertia and the temporary power surge. Both strategies will be shortly discussed in the following paragraphs.

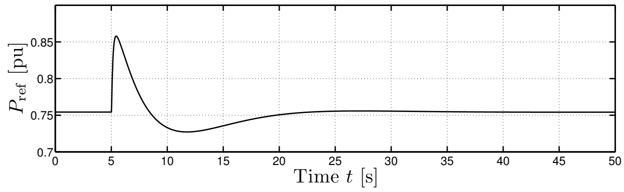


Fig. 5. Example of the synthetic inertia strategy.

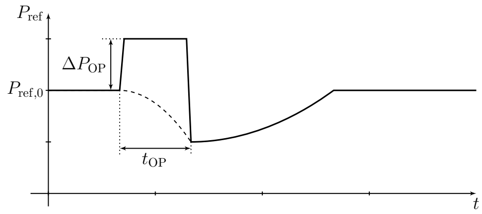


Fig. 6. Example of the temporary power surge strategy.

1) Synthetic inertia: The synthetic inertia strategy mimics the inertial response behavior of a directly-coupled synchronous generator [6]. In normal operation, the power reference P_{ref} for the power converter is determined by the Maximum Power Point Tracker (MPPT), which is given by P_{mppt}. During a frequency disturbance, an inertial response value P_{in} is added to P_{mppt} and is given by:

$$P_{\text{in}} = -K_{\text{in}} \frac{df}{dt} \tag{14}$$

When the frequency decreases, the reference power P_{ref} of the turbine is increased with P_{in}, slowing down the turbine and extracting kinetic energy from the rotor. In this way, the power output of the turbine is temporarily increased and an inertial response from the wind turbine is obtained. This strategy is called synthetic inertia since (14) resembles the behavior of a synchronous machine where kinetic energy is extracted from the rotor in case of a frequency dip. Fig. 5 shows the behavior of the synthetic inertia strategy in case of a frequency dip.

2) Temporary power surge: Another option to emulate an inertial response with wind turbines is the use of a temporary power surge [7], see Fig. 6. In the synthetic inertia strategy, the increase in power output is proportional to the rate of change of frequency. Therefore, the shape of the inertial response depends on the shape of the grid frequency f. This is not the case for the temporary power surge, where the shape of the increase in power output is determined by the temporary power surge function, as shown in Fig. 6. When a frequency dip is detected, the power output of the wind turbine is increased with ΔP_{OP} for an overproduction period t_{OP}. During this period, the power output of the turbine is higher than the mechanical power input, which causes the turbine to slow down. Afterwards, the wind turbine re-accelerates to the initial rotational speed during a period of lower power output. Then, the temporary frequency support is ended.

B. Primary frequency control

Primary control with wind turbines is achieved by adding an additional control loop to the wind turbine controller. Similar

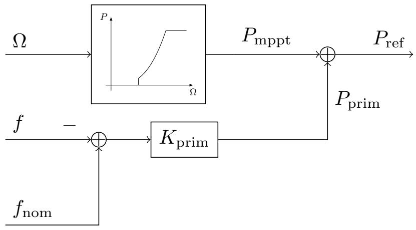
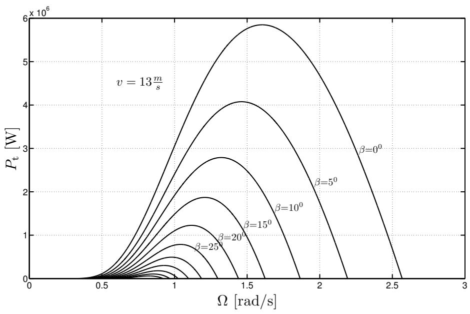
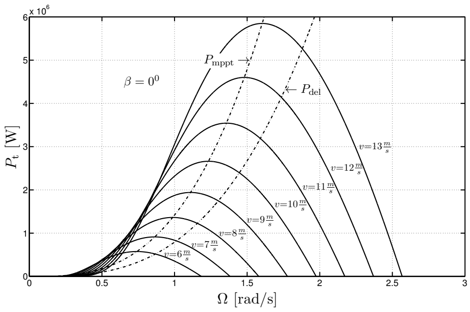


Fig. 7. Control loop for primary frequency control.



(a) Pitch control.



(b) Speed control.

Fig. 8. Deloaded operation of wind turbines.

to the primary controller in a conventional power plant, a droop controller is used in the wind turbines. The reference power for the wind turbine converter is given by [8]:

$$P_{\mathrm{ref}} = P_{\mathrm{mppt}} + K_{\mathrm{prim}} \left(f - f_{\mathrm{nom}}\right) \tag{15}$$

The control scheme is shown in Fig. 7. When the frequency exceeds the nominal frequency f_{nom}, the power output of the wind turbine is decreased. When the frequency is lower than the nominal frequency f_{nom}, the power output is increased. Decreasing the power output of a wind turbine is always possible. Increasing the power output of a wind turbine is much more difficult, as wind turbines are usually operated in their maximum power point. In order to be able to increase the power output of a wind turbine, the turbine has to maintain power reserves at any point in time, so the turbine has to be operated in deloaded mode. This results in a lower energy yield, as the turbine is not operating in the maximum power point. Another option is to add storage to the wind turbine/farm. Two strategies exist to operate a wind turbine in deloaded mode, which will be presented briefly.

1) Pitch control: This control strategy uses the pitch mechanism in wind turbines. Usually, the pitch mechanism is only used to limit the power output of the wind turbine in case of very high wind speeds. However, pitch control can also be used to obtain a power reserve for the provision of primary control. During normal operation, an increased pitch angle is used to achieve deloaded operation. In this way, the power output of the wind turbine is limited to a value lower than the maximum power output for the given wind speed, see Fig. 8a. The resulting power reserve can be delivered by decreasing the pitch angle so that the turbine can extract more power from the wind in case of a frequency dip.

2) Speed control: Another way to deload a wind turbine is by means of rotational speed control. From Fig. 8b, it is clear that there exists an optimal rotational speed Ω_{mppt} for every wind speed. This optimal rotational speed results in the maximum power output for the given speed v. However, if the turbine operates at a lower or higher rotational speed, the power coefficient C_{p} decreases and the power output is lower. The rotational speed Ω of the wind turbine is controlled by means of a power-electronic converter. By using a deloaded reference curve P_{del} for the converter, deloading of the wind turbine is achieved.

C. Secondary and tertiary frequency control

Secondary control could be provided by wind turbines, but accurate predictions of the wind speed are needed. Furthermore, a large amount of energy has to be curtailed to provide upwards power reserves. Contracted tertiary control with wind turbines is less likely, as the time scale of this service is too long to obtain reliable wind speed predictions.

IV. Voltage control with wind turbines

In this section, voltage control with wind turbines is discussed. First, the reactive power delivery capability of wind turbines is presented. Then, primary and secondary voltage control are summarized. It is important to note that, opposed to frequency control, voltage control is a local issue, so wind turbines could be very effective to tackle voltage issues.

A. Reactive power delivery capability

Especially in medium- and high-voltage grids, reactive capability is an important aspect of voltage control. Fig. 9 shows an overview of a general wind turbine capability for providing reactive power support [9]. It can be observed that even in case of zero ($P = 0$ %) or full ($P = 100$ %) power output, the wind turbine is still capable to deliver or absorb

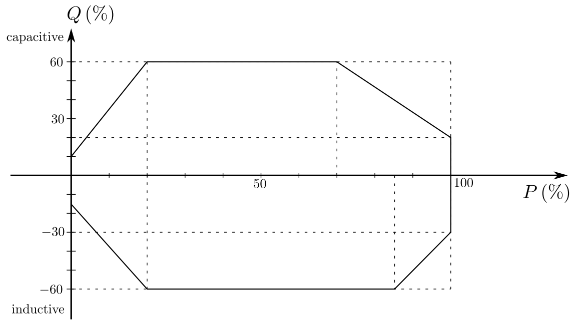


Fig. 9. Wind turbine capability for providing reactive power support.

reactive power Q. Furthermore, over a large range of active power outputs, the turbine is able to deliver maximum reactive power. It can be concluded that variable speed wind turbines have a sufficient ability to provide reactive power support.

B. Primary voltage control

As already mentioned, primary voltage control is usually achieved by means of a local (droop) controller. Due to the differences between low-, medium- en high-voltage networks, they are discussed separately.

1) HV networks: Voltage control with wind turbines in HV grids is equal to voltage control with conventional generators. The wind turbines measure the terminal voltage V_{m} and change their reactive power output accordingly. The controller is automatically and fast. The reactive power output is then given by:

$$Q = Q_0 + K_{\mathrm{Q}} \left(V_{\mathrm{nom}} - V_{\mathrm{m}}\right) \tag{16}$$

where Q_0 is the nominal reactive output and K_{Q} is determined by the slope of the Q/V characteristic, which depends on the characteristics of the wind turbine (i.e., the reactive power delivery capability). As long as the total output current does not exceed the rated current, the wind turbines are able to provide reactive power and thus voltage support. So voltage control can be regarded as a "free" service. Only if the active power output of the wind turbines has to be lowered to allow reactive power injection (when the current limits are exceeded), the service is not "free" anymore.

2) LV networks: Connection of distributed generators (e.g., small wind turbines) to the low-voltage network, will usually result in an increased voltage as active power is injected by these generators. The strong linkage between active power and voltage in resistive networks leads to these voltage problems. To solve the voltage issues, three common strategies are used: network reinforcements, hard curtailment and soft curtailment.

The historical approach to deal with voltage problems is by grid-upgrades. However, this is costly and often has a long lead time. A second option is hard curtailment. When the voltage exceeds a certain level, the distributed generator is disconnected from the grid, which is known as on-off control. This leads to a significant loss of revenue, since it is usually not necessary to disconnect the complete unit to solve the voltage problem. Furthermore, it can lead to on-off oscillations, which are detrimental for the power system. The third option is soft curtailment, by means of a P/V droop controller. When the voltage exceeds a certain threshold, the power output of the wind turbine is decreased by either speed or pitch control. If the wind turbine is operating in deloaded mode, it could also assist in voltage control in case of a decreased voltage.

3) MV networks: Voltage control in MV networks can be considered as a combination of the previous control strategies, since both P and Q injection have an influence on the terminal voltage of the wind turbine. Usually, at first instance, reactive power is controlled to solve the voltage problem. Only if this is not sufficient, the wind turbines are curtailed. Both hard curtailment and soft curtailment (P/V droops) can be used.

A more advanced method is to use a combination of both P/V and Q/V droops to control the voltage [10]. When using both droop controllers, it is key how to coordinate these controllers to avoid unnecessary loss of renewable energy injection, reactive power fines and overly large grid losses.

C. Secondary and tertiary voltage control

Also secondary control is possible with wind turbines, but it is less important. In secondary control, the set points of the Q/V (or P/V) droops of the generators in one zone are changed in order to control the voltage of one pilot node in this zone to a reference value. This is completely analogous to the secondary voltage control in conventional generators. Another option is to send directly new set points for P and Q to the wind turbines, but this leads to communication delays and decreased robustness of the system [9]. Tertiary control is completely equivalent to the conventional case.

V. Conclusions

In this paper, the ability to provide ancillary services with wind turbines is discussed. Two important services, frequency and voltage control, are considered. To obtain a similar inertial response from wind turbines as from conventional units, emulated inertia should be used. Primary frequency control can be provided if wind turbines are operated in deloaded mode, or storage is included in the wind farm. As variable speed wind turbines have a converter with the ability to inject and absorb reactive power, voltage control can be provided by wind turbines in low-, medium- and high-voltage grids.

Acknowledgment

The research of T. L. Vandoorn and J. D. M. De Kooning is funded by the Special Research Fund (BOF) of Ghent University (Belgium). This research has been carried out in the frame of the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office (IAP-VII-02).

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